THE CLUSTERING OF IRAS GALAXIES

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ABSTRACT

We investigate the clustering of galaxies in the QDOT redshift survey of IRAS galaxies. We find that the two-point correlation function is well approximated by a power-law of slope -1.11 ± 0.09, with clustering length $3.87 \pm 0.32 h^{-1}$ Mpc* out to pair separations of $\sim 25 h^{-1}$ Mpc. On scales larger than $\sim 40 h^{-1}$ Mpc, the correlation function is consistent with zero. The *rms* fluctuation in the count of QDOT galaxies above the Poisson level in spheres of radius $8 h^{-1}$ Mpc is $\sigma_8^{IRAS} = 0.58 \pm 0.14$, showing that fluctuations in the distribution of IRAS galaxies on these scales are smaller than those of optical galaxies by a factor of about 0.65, with an uncertainty of $\sim 25\%$. We find no detectable difference between the correlation functions measured in redshift space and in real space, leading to a 2σ limit of $b_{IRAS}/\Omega^{0.6} > 1.05$, where b_{IRAS} is the bias factor for IRAS galaxies and Ω is the cosmological density parameter. The QDOT autocorrelation function calculated in concentric shells increases significantly with shell radius. This difference is more likely due to sampling fluctuations than to an increase of the clustering strength with galaxy luminosity, but the two effects are difficult to disentangle; our data allow at most an increase of $\sim 20\%$ in clustering strength for each decade in luminosity. For separations greater than $\sim 3 h^{-1}$ Mpc, the cross-correlation function of Abell clusters (with Richness $R \geq 1$) and QDOT galaxies is well approximated by a power-law of slope -1.81 ± 0.10, with clustering length $10.10 \pm 0.45 h^{-1}$ Mpc, and no significant signal beyond $\gtrsim 50 h^{-1}$ Mpc. This cross-correlation depends only weakly on cluster richness.

Key words   Galaxies: clustering - dark matter - large scale structure of the Universe

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* Throughout this paper h denotes the Hubble constant in units of $100 \, \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$.

§1. INTRODUCTION

The distribution of matter in the Universe on large scales provides one of the strongest constraints on models of galaxy formation. Several surveys have been used to measure galaxy clustering on scales between $10h^{-1}$ Mpc and $50h^{-1}$ Mpc (Maddox *et al.* 1990 (APM); Efstathiou *et al.* 1990, Saunders *et al.* 1991 (QDOT); Fisher *et al.* 1993 (1.2Jy); Vogeley *et al.* 1992 (CfA2); Loveday *et al.* 1992a (Stromlo/APM)). In addition, estimates of the mass and abundance of galaxy clusters (White, Efstathiou and Frenk 1993) and measurements of large scale velocity flows (Vittorio *et al.* 1986, Lynden-Bell *et al.* 1988, Strauss *et al.* 1993) have been used to constrain the mass distribution on scales of ~ 10 and up to $\sim 100h^{-1}$ Mpc respectively. On scales comparable to the present Hubble radius, temperature fluctuations in the microwave background can be used as probes of primordial fluctuations in the gravitational potential (Smoot *et al.* 1992).

In this paper, we analyse the clustering properties of the QDOT "one-in-six" redshift survey of IRAS galaxies (Lawrence *et al.* 1993). There are 2163 galaxies in this survey which were chosen by randomly sampling at a rate of one-in-six from galaxies selected from the IRAS point source catalogue with 60μ flux greater than 0.6Jy at galactic latitudes $|b| > 10°$. Regions of sky heavily contaminated by sources in our own galaxy and the IRAS coverage gaps are delineated by a mask which excludes about 10% of the sky at $|b| > 10°$. The parent galaxy catalogue is described in detail by Rowan-Robinson *et al.* (1991). The QDOT survey covers 9.31 steradians (74% of the sky) and samples the density field in the Universe to a redshift $z \approx 0.05$, well beyond the Local Supercluster. The survey is particularly well suited to investigations of large scale structure because it uniformly samples a large-volume of the universe.

A variety of techniques have been used to characterise large-scale clustering in the QDOT survey. Efstathiou *et al.* (1990) and Saunders *et al.* (1991) estimated the variance of QDOT galaxy counts-in-cells and found that the clustering on scales $\gtrsim 20h^{-1}$ Mpc exceeds that expected in simple versions of the cold dark matter (CDM) model. Moore *et al.* (1992) studied the topology of the galaxy distribution and showed that the power spectrum is consistent with that of a Gaussian random field with the slope inferred from the counts-in-cells analyses. These studies complement each other and give consistent results, even though the estimation techniques and weighting schemes are different.

The analysis of IRAS galaxy correlations presented here is directed at three distinct questions:

[A] Although the above analyses of the QDOT sample have revealed a discrepancy with the standard CDM model, they assume that the galaxy luminosity function is universal and independent of position and local environment. Babul and White (1991), Silk (1992) and Bower *et al.* (1993) have considered alternative non-linear biasing schemes which could give rise to enhanced large scale power in the galaxy distribution. Such effects, if present, complicate the interpretation of clustering data and could remove the discrepancy with the

standard cold dark matter model. Spatial modulations in the efficiency of galaxy formation could be tested by measuring the two-point correlation function as a function of luminosity or morphological type. In this paper we investigate how the correlation function of IRAS galaxies depends on luminosity.

[B] Saunders *et al.* (1992) cross-correlated the QDOT redshift catalogue with its parent IRAS catalogue, which contains the positions of over 12000 galaxies, to compute a cross-correlation function as a function of metric separation. This function is related to the spatial correlation function, $\xi(r)$, by a Limber-like equation which can be inverted numerically. Comparing this determination of $\xi(r)$ with the redshift-space correlation function measured in this paper yields information about the clustering distortion caused by the peculiar velocities of galaxies and hence about the relative clustering strength of galaxies and mass on large scales (Kaiser 1987).

[C] Several authors have pointed out that IRAS galaxies appear more weakly clustered than optically selected galaxies on small scales (e.g. Davis *et al.* 1989; Saunders *et al.* 1992; Strauss *et al.* 1992). In addition, the cores of rich clusters appear to contain very few IRAS galaxies. Since these are predominantly late type disk systems, these observations may simply reflect the morphology-density relation. In an attempt to understand their environments, we study how IRAS galaxies are distributed with respect to rich Abell clusters by cross-correlating the positions of the QDOT galaxies with a sample of rich galaxy clusters. The nature of the IRAS luminosity function creates a tail of high redshift QDOT galaxies and allows us to directly measure this relation in redshift space. We compare these results with those of Lilje and Efstathiou (1988) who measured the projected cross-correlation function between optically selected galaxies and Abell clusters.

In the next section we calculate the two-point correlation function of the QDOT redshift survey. We compare different weighting schemes and methods to determine the errors in $\xi(s)$ using artificial IRAS catalogues constructed from numerical simulations of the CDM model. From Monte-Carlo simulations and bootstrap resampling, we show how uncertainties in estimates of the correlation function can be reliably obtained from the data. In Section 3 we compare the redshift-space and real-space correlation functions from numerical simulations and the QDOT survey in an attempt to quantify the distortions produced by large-scale streaming motions. In Section 4 we subdivide the data by distance and luminosity to investigate the large scale clustering properties of these galaxies and to test for luminosity dependent clustering. In Section 5 we cross-correlate the QDOT data with samples of Abell clusters of different richness. Our results are summarised in Section 6 where we also compare with previous analyses of these data.

§2. THE TWO-POINT CORRELATION FUNCTION

The two-point correlation function of a redshift survey, $\xi(s)$, is defined in terms of the joint probability of finding galaxies separated by distance s in redshift space and lying

in volume elements δV_1 and δV_2:

$$\delta P_{12} = \overline{n}^2 (1 + \xi(s)) \delta V_1 \delta V_2 \ , \tag{1}$$

where $\overline{n}$ is the mean density. To calculate $\xi(s)$ for the QDOT survey we use two different estimators, one introduced by Davis and Peebles (1982) and the other by Hamilton (1993). The first of these is:

$$1 + \xi(s) = \frac{DD(s)}{DR(s)} \left(\frac{N_R}{N_D} \right) \ , \tag{2a}$$

where $DD(s)$ is the weighted pair count of galaxies in an interval of separation centred on s and $DR(s)$ is an analogous weighted count of pairs consisting of a galaxy and a point chosen from a large random catalogue with the same sky coverage and mean redshift distribution as the QDOT survey. N_R and N_D are weighted sums over the random and data points given by equation (5) below. Hamilton (1993) has proposed a slightly different estimator which is less sensitive to uncertainties in the mean density:

$$1 + \xi(s) = \frac{DD(s)RR(s)}{DR(s)DR(s)} \ , \tag{2b}$$

where $RR(s)$ is the weighted count of pairs of points in the random catalogue.

For both these estimators the number of data-data, data-random and random-random pairs are calculated as

$$DD, DR \ or \ RR = \sum_i \sum_j \frac{1}{(1 + 4\pi J_3(s_{ij})\phi(s_i))} \frac{1}{(1 + 4\pi J_3(s_{ij})\phi(s_j))} \ , \tag{3}$$

where the sum over i extends over the entire sample and the sum over j only over those sample members within the specified distance bin from the ith member; $\phi(s_i)$ is the mean galaxy density at distance s_i; s_{ij} is the separation, $|\underline{s}_i - \underline{s}_j|$, between the ith and j^{th} sample members and

$$J_3(s_{ij}) = \int_0^{s_{ij}} s^2 \xi(s) ds \ . \tag{4}$$

The weights in equation (3) are chosen to give an approximately minimum variance estimate of $\xi(s)$ on large scales (c.f. Efstathiou 1988, Loveday et al. 1992a, Saunders et al. 1992). This weighting scheme has the desirable property of switching from volume weighting at small distances where clustering dominates the error in ξ, to uniform weighting per galaxy at large separations, as is appropriate for a Poisson point process.

The number densities are calculated as

$$N_D(s) = 1/V_w \sum_{data,i} w_i(s) \ , \quad N_R(s) = 1/V_w \sum_{random,i} w_i(s) \ , \tag{5}$$

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where

$$w_i = \frac{1}{1 + 4\pi J_3^{max}\phi(s_i)} \; ,$$ (6)

and J_3^{max} is the maximum value of the integral J_3 defined in equation (4) and is derived from the models of $\xi(s)$ described below (see for example, Loveday *et al.* 1992b). V_w is the weighted volume:

$$V_w = 4\pi \int s^2 \phi(s)w(s)ds \; .$$ (7)

For this analysis we require prior knowledge of the galaxy selection function, $\phi(s)$, and a model for $\xi(s)$ itself. We calculate the selection function by integrating the luminosity function of IRAS galaxies (solution (19) of Saunders *et al.* 1990). Since the fractional error in $1+\xi(s)$ is proportional to $\Delta\phi/\phi$, uncertainties in the mean density at distances $\gtrsim 100h^{-1}$ Mpc can lead to errors in $\xi(s)$ of similar size to the signal that we are trying to measure. Saunders *et al.* (1991) determined the mean density of the QDOT survey to within $\pm 5\%$, an uncertainty which arises mainly from small number statistics and systematic effects due to density fluctuations of order the survey size. Furthermore, Saunders *et al.* (1990) found evidence for evolution in the number density of IRAS galaxies even at relatively low redshifts, $n \propto (1+z)^{6.7\pm 2.3}$. The uncertainty in this estimate could systematically bias our estimates of the correlation function, so in what follows we explicitly include the effects of evolution. We find that for the most part these effects are negligible.

To compute J_3 for the weighting scheme of equation (3) we use the linear theory correlation function for models similar to the standard scale-invariant CDM model. The shapes of the power-spectra in these models are characterised by a parameter, Γ, which is simply $\Gamma = \Omega h$ in adiabatic, scale invariant CDM models with low baryon density. Lower values of Γ correspond to models with more power on large scales (see Efstathiou, Bond and White (1992) for a discussion of constraints on the parameter Γ). We consider the values $\Gamma = 0.5$ and 0.2. These models are normalised such that the variance of the density field in top hat spheres of radius $8h^{-1}$ Mpc equals 0.7, consistent with the counts-in-cells results of Efstathiou *et al.* (1990) and Saunders *et al.* (1991).

To test different weighting schemes and other statistics, we constructed artificial QDOT catalogues from the ensemble of 5 CDM N-body simulations described by Frenk *et al.* (1990). At the output time chosen, the rms mass fluctuation in spheres of radius $8h^{-1}$ Mpc, $\sigma_8^{\rho} = 0.5$, consistent with the model independent determination of σ_8^{ρ} by White, Efstathiou and Frenk (1993). Using the techniques introduced by White *et al.* (1987), based on the "high-peak" model of biased galaxy formation, we identified galaxies in the simulations and constructed catalogues with the same flux limit, sampling rate, masked region and mean selection function of the QDOT survey. The average (real-space) rms fluctuation in the galaxy count in these catalogues is $\sigma_8^g = 0.76$, corresponding to a biasing parameter, $b \equiv \sigma_8^{\rho}/\sigma_8^g = 1.5$. This is only slightly higher than the value inferred for QDOT

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galaxies in an $\Omega = 1$ universe by Kaiser *et al.* (1991) from an analysis of peculiar velocity fields. In all subsequent calculations we limit our samples to distances less than $300h^{-1}$ Mpc and we use random catalogues containing 10^5 galaxies.

Figure 1a shows mean values of the redshift-space $\xi(s)$ (ie using the redshift-distance rather than the true distance to each galaxy) for the artificial catalogues, estimated from equation (2a). Results with three different weighting schemes are displayed: equation (3) with J_3 obtained by integrating the linear theory prediction for $\xi(s)$ with $\Gamma = 0.5$ and 0.2; equation (3) assuming a constant $4\pi J_3 = 3000$; and equal weighting for all galaxies. The dashed line shows the linear theory prediction for the CDM ($\Gamma = 0.5$) correlation function, corrected for redshift-space distortions as discussed in Section 3.

Our estimates of $\xi(s)$ do not depend strongly on our assumed weighting scheme even on large scales. Furthermore, on large scales the estimates from the simulations agree very well with the linear theory prediction. Figure 1b shows the mean of $\xi(s)$ estimated from equation (2a) (with J_3 from linear theory), together with 1σ errors determined from the scatter in the 5 different realisations. It is interesting to see how reliably we can estimate the errors in $\xi(s)$ from a single sample. To this effect we plot to the left of each point in Figure 1(b) the statistical errors, $\Delta\xi = (1+\xi(s))/\sqrt{N_D}$, and to the right of each point, the 1σ errors from 100 bootstrap realisations of a single artificial catalogue. The different error estimates give similar results with no measurable bias. Since the (J_3-weighted) statistical errors are the simplest to calculate, we shall use them in the remainder of this paper.

Figure 2a shows the correlation function of the QDOT survey calculated from equation (2b), with the $\Gamma = 0.2$ linear theory prediction for $J_3(s_{ij})$. The open and filled circles show the effect of including and ignoring evolution in the number density with redshift. Our estimates of the correlation function are very stable, even though the density of galaxies in the random catalogue at $100h^{-1}$ Mpc (approximately the median distance) increases by $\sim 25\%$ when evolution is included. Figure 2b shows correlation functions, this time estimated using equation (2a). (The symbols are as in Figure 2a.) Both estimators give very similar results.

The data in Figures 2a and 2b can be approximately described by a power-law on scales $\lesssim 25h^{-1}$ Mpc, as expected from the angular correlation function of IRAS galaxies which is very well fit by a power-law on scales 0.1 to 5 h^{-1} Mpc. The small curvature apparent in the QDOT data can be explained by the combined effect of peculiar velocities and observational errors in the velocity determinations. Both of these enhance the correlations on scales of a few hundred kilometers per second and suppress them on smaller scales. Ignoring for the moment the effect of large-scale galaxy bulk flows, we can model these small-scale effects by assuming a form for the distribution of relative velocities between galaxy pairs. If ξ'_r denotes the spatial correlation function in real space (unaffected by velocity errors and peculiar velocities on small scales), then the observed correlation function in redshift space will be the direction-averaged convolution of $\xi'_r(s)$ and the velocity

distribution function, $f(v)$, *i.e.*

$$\xi_s(s) \approx \frac{1}{2\pi} \int_{-1}^{1} \int_{-\infty}^{\infty} \xi'_r(\sqrt{s^2 + v^2 - 2sv\mu}) f(v) \, dv d\mu \ , \tag{8}$$

where we have ignored any dependence of the shape of $f(v)$ on pair separation and we have ignored distortions caused by streaming motions (see equation 10 below) which are small if $\xi \gtrsim 1$ (see *e.g.* Bean *et al.* 1983). We assume that $\xi'_r(r) = (r/r_0)^{-\gamma}$ and that $f(v)$ is a Gaussian with dispersion σ. We then find the values of r_0 and γ that give the best fit between $\xi_s(s)$ and the data points in Figure 2a. Adopting $\sigma = 250 \text{km s}^{-1}$, a χ^2 fit to the data out to pair separations of $25 \text{h}^{-1} \text{Mpc}$ gives:

$$r_0 = 3.87 \pm 0.32 \text{h}^{-1} \text{Mpc}, \quad \gamma = 1.11 \pm 0.09 \ . \tag{9}$$

Very similar values are obtained if instead we take $\sigma = 400 \text{km s}^{-1}$. Table 1 summarises our correlation function results. Both $\xi_s(s)$ and $\xi'_r(s)$ are plotted in Figure 2a.

We have also plotted in Figure 2a the average correlation function in redshift space for our five artificial catalogues, as well as the linear theory prediction of the *real-space* correlation function for a model with $\Gamma = 0.2$. (As discussed below, redshift-space distortions are negligible in the latter case.) On scales $\gtrsim 10 \text{h}^{-1}$ Mpc, the data show the same excess clustering relative to the standard CDM model seen in previous studies. The $\Gamma = 0.2$ linear theory model provides a good match to the data on scales $s \simeq 10 \text{h}^{-1}$ Mpc. This model also gives a good match to the shape of the large-scale angular correlation function of optical galaxies determined from the APM survey (Maddox *et al.* 1990). Beyond $s \simeq 40 \text{h}^{-1}$ Mpc, the QDOT correlations are consistent with zero.

In Figure 2b, we plot correlation functions for three subsamples of the QDOT survey, volume-limited at 40, 80 and 120 h^{-1} Mpc, containing 169 , 295 and 298 galaxies respectively. On small scales, the various curves are roughly consistent with one another. However, on scales $> 10 \text{h}^{-1}$ Mpc, $\xi(s)$ estimated from the full survey has a somewhat larger amplitude than $\xi(s)$ estimated from the first two volume-limited subsamples. We shall see below that this discrepancy is caused by a small but systematic increase of clustering amplitude with distance.

§3. COMPARISON OF THE REAL AND REDSHIFT SPACE CORRELATION FUNCTIONS

We have measured the correlation function of QDOT galaxies in redshift space. According to linear perturbation theory, streaming motions cause the redshift-space correlation function, ξ_s, to be enhanced over that measured in real space, ξ_r, by a factor

$$f = 1 + \frac{2}{3} \frac{\Omega_0^{0.6}}{b} + \frac{1}{5} \frac{\Omega_0^{1.2}}{b^2} \ , \tag{10}$$

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(Kaiser 1987) where we have assumed that in the linear regime the correlation function of IRAS galaxies is related to the mass correlations, $\xi_\rho(r)$, by $\xi_r(r) = b^2\xi_\rho(r)$ (*i.e.* linear biasing; see Davis *et al.* 1985).

To test the validity of this formula in the regime probed by our data and to assess our ability to measure f from the QDOT survey, we first calculate the two-point correlation function in real- and redshift-space for our artificial catalogues. The filled and open squares in Figure 3 show the average real-space and redshift-space correlation functions respectively for our 5 fully-sampled catalogues. The lower solid line shows a polynomial fit to the correlation funtion in real space, and the upper curve shows this same polynomial fit shifted vertically by the expected factor of 1.53 as indicated by equation (10) for $b = 1.5$. This line gives a surprisingly good match to the redshift-space correlation function, even on scales where the clustering pattern is mildly non-linear.

The results for the artificial one-in-six catalogues are less encouraging. The red-shift - space correlation function lies systematically above the (fully-sampled) real-space function, but the statistical errors are too large for this effect to be detected with high significance. In practice, the uncertainties in estimating the real-space correlation function are likely to exacerbate this problem. An estimate of f may be obtained by minimizing the χ^2 difference between the real- and redshift-space correlation functions. For the fully sampled case this yields $f = 1.6 \pm 0.2$ and, for the one-in-six redshift space sampling, it yields $f = 1.7 \pm 0.4$. The quoted errors are the average of the errors determined assuming maximum and minumum correlation between data points.

For the QDOT data, the correlation function in real space may be derived from the cross-correlation function of the redshift sample with its fully sampled parent catalogue, computed as a function of projected separation σ. Saunders *et al.* (1992) calculated an integral over ξ_r,

$$\Xi(\sigma) = \int_{-\infty}^{\infty} \xi_r\left(\sqrt{y^2 + \sigma^2}\right) \, dy, \tag{11}$$

in logarithmic bins in σ. If ξ_r is approximated as a set of steps, $\xi_r(r) = \xi_i$ for $s_i < r < s_{i+1}$, we can integrate equation (11) to give:

$$\Xi_i = 4/3\Big[\xi_i(s_{i+1}^2 - s_i^2)^{3/2}$$

$$+ \sum_{j=i}^{\infty} \xi_j((s_{j+1}^2 - s_i^2)^{3/2} - (s_j^2 - s_i^2)^{3/2} - (s_{j+1}^2 - s_{i+1}^2)^{3/2} + (s_j^2 - s_{i+1}^2)^{3/2})\Big]. \tag{12}$$

The redshift-space analogue of $\Xi(\sigma)$ [denoted by $\Xi_s(\sigma)$] can be calculated numerically from equation (11) and our estimates of ξ_s for the QDOT sample. We assume $\xi_s(s) = 0$ for $s > 50h^{-1}$ Mpc and estimate errors by splitting up the survey into octants and measuring the scatter in the estimate of Ξ_s for each octant.

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In Figure 4a we compare the resulting Ξ_s with the Saunders *et al.* estimate of Ξ_r. The two estimates are in good agreement and show no evidence for any distortion of the correlation function measured in redshift space. To quantify this, we determine f in equation (10) as above, by minimising the χ^2 difference between ξ_s and $f\xi_r$ in the range $5-30h^{-1}$ Mpc. This gives $f = 0.8 \pm 0.5$ (1σ error). A possible concern with this approach is that Ξ_s is an integral over ξ_s to large distances (formally to infinity) and the errors in ξ_s at large separations can introduce correlated errors in Ξ_s on all scales. We can check whether this is a problem by comparing our measurements of ξ_s with estimates of ξ_r derived by differentiating Ξ numerically. This comparison is carried out in Figure 4b. As before, we estimate uncertainties from the results for each octant. Differentiation introduces noise into ξ_r, but the final answer for the ratio of amplitudes is consistent with our previous estimate, *i.e.* $f = 1.0 \pm 0.4$ (1σ error) over the range $5 - 30h^{-1}$ Mpc. (Similar results are obtained if the fits are done over the range $10 - 30h^{-1}$ Mpc.) We adopt this value as our final answer. This result sets a 2σ *lower* limit of $b_{IRAS}/\Omega_0^{0.6} > 1.05$, close to the value $b_{IRAS}/\Omega_0^{0.6} = 1.2 \pm 0.2$ determined by comparing measurements of the peculiar velocity of the Milky Way, and other galaxies, with the motions inferred from the spatial distribution of QDOT galaxies (Rowan-Robinson *et al.* 1990, Kaiser *et al.* 1991). A similar limit on $b/\Omega_0^{0.6}$ has been derived from the lack of redshift-space distortion in the Stromlo/APM redshift survey of optically selected galaxies (Loveday *et al.* 1992a).

The are two reasons why our measurement of f is so uncertain. Firstly, we are attempting to measure small differences between the much larger measured quantities, $1 + \xi_s$ and $1 + \xi_r$, and, as the artificial catalogues show, this requires highly accurate estimates. Secondly, the test makes very great demands on the "fair sample" hypothesis: one must have not only a fair sample of superclusters, but a fair sample of *orientations* of superclusters as well. Nevertheless, our results suggest that future surveys of tens of thousands of galaxies should lead to constraints on the amplitude of mass fluctuations determined from the clustering distortion which are at least as useful as present constraints derived from streaming velocities.

§4. LARGE SCALE INHOMOGENEITIES IN THE DISTRIBUTION OF IRAS GALAXIES

The counts-in-cells analysis of Efstathiou *et al.* (1990) showed a large variance in the counts of QDOT galaxies in cells at a distance $\approx 100h^{-1}$ Mpc. Maps of the galaxy distribution show several large superclusters at this distance, including the prominent Hercules structure (Saunders *et al.* 1991, Moore *et al.* 1992). To investigate this further, we have estimated ξ_s from the QDOT survey in a series of concentric shells of increasing distance from the observer. Figure 5 shows the correlation function of galaxies measured in three shells of radii $5 - 50h^{-1}$ Mpc, $50 - 100h^{-1}$ Mpc and $100 - 300h^{-1}$ Mpc, using the two different estimators in equation 2. There are 561, 636 and 723 galaxies in these

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shells, with median luminosities $2.1 \times 10^9 h^{-2} L_\odot$, $8.6 \times 10^9 h^{-2} L_\odot$, and $3.4 \times 10^{10} h^{-2} L_\odot$ respectively.

On scales $\lesssim 10 h^{-1}$ Mpc there is no apparent difference between the clustering properties of galaxies as a function of shell distance. On larger scales there is a systematic increase of clustering strength with shell distance and it is clear that most of the clustering signal at separations $\gtrsim 10 h^{-1}$ Mpc comes from the most distant shell ($s \geq 100 h^{-1}$ Mpc). This result is independent of our choice of estimator for ξ_s, although Hamilton's estimator gives somewhat stronger clustering in the nearest shell at large pair separations. With the present data set we are unable to determine whether the apparent increase in clustering strength with shell distance is due to sampling fluctuations in the different volumes or whether it is due to a dependence of the shape of the correlation function on luminosity.

To investigate the possibility of luminosity bias further, we have repeated the projected correlation analysis of Saunders *et al.* (1992), this time looking for luminosity dependence. We split the QDOT survey into four luminosity bins at $\log(L/h^{-2} L_\odot) < 9.25, 9.25 - 9.75, 9.75 - 10.25, > 10.25$, and find the projected cross-correlation function with the fully sampled parent catalogue in each case. The results are shown in Figure 6. To quantify any dependence of the amplitude of the correlation function on L, we fitted the data points in the range $5 - 30 h^{-1}$ Mpc with a power-law of the form, $(s/s_0')^{\gamma'}$, where s_0' depends on the median luminosity in each luminosity interval:

$$s_0' \propto L_{med}^\alpha, \quad \gamma = \text{const} . \tag{13a}$$

The resulting best fit is

$$\alpha = 0.033 \pm 0.025 \quad (1\sigma \text{ error}). \tag{13b}$$

This statistic provides a constraint on the variation of the amplitude of $\xi(s)$ with luminosity, giving a 2σ upper limit of a 20% increase in s_0' for each decade increase in luminosity. Although the cross-correlation function is less sensitive than the autocorrelation function to variations in clustering strength with luminosity, our results show that much of the variation of $\xi_s(s)$ with shell radius seen in Figure 5 must arise from sampling fluctuations rather than luminosity dependence. Our data are nevertheless consistent with a weak dependence of the clustering amplitude with luminosity.

§5. THE CLUSTER-GALAXY CROSS-CORRELATION FUNCTION

The prominent galaxy clusters apparent in optical maps are far less conspicuous in maps of IRAS galaxies (*e.g.* Figure 1 in Saunders *et al.* 1991). We can quantify this difference by comparing the cross-correlation function, $\xi_{cg}(s)$, of Abell clusters with IRAS and optical galaxies respectively. The bright tail in the luminosity function of IRAS galaxies gives rise to a population of high redshift galaxies in the QDOT survey which overlaps

samples of Abell clusters. As a result, $\xi_{cg}(s)$ can be estimated in a fairly straightforward fashion. We use the sample of 822 Abell clusters with measured redshifts in the compilation of Abell *et al.* (1989), which has a median depth of $\sim 300h^{-1}$ Mpc and divide the clusters into different (optically determined) richness classes. The subsamples contain 467 clusters of richness $R \geq 1$ and 209 clusters of richness $R \geq 2$.

We estimate $\xi_{cg}(s)$ using the analogue of equation (2a),

$$1 + \xi_{cg}(s) = \frac{CG(s)}{CR(s)} \left(\frac{N_R}{N_D} \right) , \qquad (14)$$

where $CG(s)$ is the weighted pair count of Abell clusters lying in an interval of separation centred on s from a QDOT galaxy, and $CR(s)$ is an analogous weighted count of pairs consisting of a cluster and a point chosen from a large random catalogue (containing 10^5 points) with the same sky coverage and mean redshift distribution as the QDOT survey. We use a similar weighting scheme to that described in Section 2, with number densities, N_R and N_D, given by equation (5). To calculate J_3 we adopt the cluster-galaxy cross correlation function measured by Lilje and Efstathiou (1988).

The filled circles in Figure 7 show our estimate of the cross-correlation function, $\xi_{cg}(s)$, between the full sample of Abell clusters and the QDOT survey. The 1σ error bars shown were obtained by estimating $\xi_{cg}(s)$ for four independent subsamples of the data and are quite similar to the Poissonian errors of the J3-weighted pair counts. Beyond $3h^{-1}$ Mpc, the cluster-galaxy cross-correlation functions are well fit by a power-law of the form $\xi_{cg}(s) = (s/s_\circ)^\gamma$. For clusters with richness $R \geq 1$ we find $s_\circ = 10.10 \pm 0.45 h^{-1}$ Mpc and $\gamma = -1.75 \pm 0.10$, consistent with the results of Mo *et al.* (1993) determined from our data. The amplitude of the cross-correlation is higher for the $R \geq 1$ than for $R \geq 0$ clusters, but there is no detectable increase in amplitude for higher cluster richness. Table 1 summarises these results using formal χ^2 fits to the data beyond $3h^{-1}$ Mpc.

At smaller separations, $1.5h^{-1}$ Mpc$\leq s \leq 3h^{-1}$ Mpc, the number of clustered QDOT galaxies drops. The shape of ξ_{cg} on small scales is affected by a combination of velocity errors and peculiar motions of galaxies in clusters which smear out intrinsic correlations. (This is analogous to the smearing of the autocorrelation function described in Section (2)). Modelling these effects requires knowledge of the velocity distribution function and can, in principle, be performed using the techniques discussed in Section 2 in connection with the galaxy - galaxy correlation function. For example, assuming a Gaussian distribution of cluster galaxy velocities of width $\sigma = 800$km s^{-1} (close to the median 1-D velocity dispersion for $R \geq 1$ Abell clusters), we find a best fit power-law with parameters, $s_\circ = 7.95 \pm 0.10 h^{-1}$ Mpc, and, $\gamma = -1.56 \pm 0.38$, for $R \geq 1$ clusters.

For comparison with optical galaxies we refer to Lilje and Efstathiou's (1988) estimate of the projected cross-correlation function between Abell clusters of richness class $R \geq 1$ and the Lick galaxy counts (Shane and Wirtanen 1967). These authors estimated $\xi_{cg}(s)$ by inverting a Limber-like equation and found a power-law behaviour for $\xi_{cg}(s)$ with exponent -2.21 ± 0.04 and clustering length, $s_\circ = 8.8 \pm 0.6 h^{-1}$ Mpc. This result is plotted

as a dashed line in Figure 7. Beyond $s \simeq 3h^{-1}$ Mpc, the cross-correlation functions for both optical and IRAS galaxies with clusters of richness $R \geq 1$ have comparable amplitudes, but different slopes. At small separations, ξ_{cg} for optical galaxies continues to increase at separations $\lesssim 0.5h^{-1}$ Mpc, and rises significantly above ξ_{cg} for QDOT galaxies. Note that the QDOT counts in this regime are affected by velocity broadening. Nevertheless, a difference in the relative distributions of optical and IRAS galaxies near the centres of rich clusters is expected from Dressler's (1980) morphology-density relation.

§6. DISCUSSION AND CONCLUSIONS

We have carried out a clustering analysis of the QDOT survey of IRAS galaxies, focussing on three specific issues: (i) the form of the two-point correlation function on large scales and its dependence on galaxy luminosity, (ii) the amplitude of the redshift-space distortion of the correlation function and (iii) the relative distributions of IRAS and optical galaxies around Abell clusters.

At pair separations less than $25h^{-1}$ Mpc, the two-point correlation function of QDOT galaxies is well approximated by a power-law of the form $\xi(s) = (s/s_{\circ})^{\gamma}$, with $\gamma = -1.11 \pm 0.09$ and clustering length, $s_{\circ} = 3.87 \pm 0.32h^{-1}$ Mpc. (These numbers take into account the smearing due to small scale peculiar velocities and measurement errors, and are unaffected by luminosity/density evolution of IRAS galaxies.) Beyond $s \simeq 40h^{-1}$ Mpc, our data are consistent with $\xi(s) = 0$. This result agrees well with the correlation function determined for two other redshift surveys of IRAS galaxies, the 2 Jy survey of Strauss et $al.$ (1990) and the 1.2 Jy survey of Fisher et $al.$ (1994). IRAS galaxies appear to be slightly less strongly clustered than optical galaxies on small scales. The difference decreases on larger scales reflecting the shallower slope of the IRAS autocorrelation function. This is consistent with the results of Loveday et $al.$ (1992a), who find that the variances in the counts of optical and IRAS galaxies are similar, $\sigma_{opt}^2/\sigma_{IRAS}^2 = 1.2 \pm 0.3$, on scales $\gtrsim 20$ h^{-1} Mpc.

We can compare our results with the analyses of Efstathiou et $al.$ (1990) and Saunders et $al.$ (1991), who give the variance of counts-in-cells in the QDOT survey as a function of cell-size, using two different estimation procedures. This variance is related to the correlation function by a double integral over the cell volume V:

$$\sigma^2 = \int_V \xi(s_{1,2})dV_1 dV_2/V^2 \ . \tag{15}$$

In Table 2 we list the results of evaluating this integral over cubical cells of side ℓ using a cubic spline fit to (the uncorrected) ξ_s. The numbers in brackets are approximate errors estimated from the integral using fits to the top and bottom of the error bars for the J_3-weighted estimate of ξ_s plotted in Figure 2. (This clearly gives a rather pessimistic

estimate since it assumes that the errors in the estimates of ξ_s in different bins are 100% correlated.) The third column of Table 2 gives the counts-in-cells results of Efstathiou *et al.* In cells of length 30 h^{-1} Mpc and 40 h^{-1} Mpc, our estimated variances are just within the 95% errors quoted by Efstathiou *et al.*, but in the other cells the agreement is good. For comparison, in column 4 we list the counts-in-cells for an optically selected catalogue of galaxies by Loveday *et al.* (1992a). In columns 5 and 6 we give the expected variances for the theoretical models considered in Section 2. For the standard CDM model we use the procedure employed for the real data and integrate the correlation function determined from our artificial catalogues (cf Figure 2a). For the $\Gamma = 0.2$ model, we simply integrate the (real-space) linear theory correlation function. On large scales, the standard CDM model gives variances which fall outside of the 95% error limits of the data. These results agree with the analysis of the 1.2 Jy survey by Fisher *et al.* (1994).

We find no detectable difference between estimates of the QDOT autocorrelation function in real and redshift space over the range where we have measured these functions. This is not surprising – our artificial catalogues show that the redshift-space distortion would be detectable in a fully-sampled version of the QDOT catalogue (if $b = 1.5$) but in our sparsely sampled survey the signal is swamped by statistical errors. Neverthelss, we are able to set a 2-sigma lower limit of $b^{IRAS}/\Omega^{0.6} > 1.05$, consistent with independent estimates based on studies of the peculiar velocity filed (see for example, Kaiser *et al.* 1991, Dekel *et al.* 1992).

Integrating ξ_s over volume leads to an estimate of $\sigma_8^{IRAS} = 0.58 \pm 0.14$ for the *rms* count of IRAS galaxies in top hat spheres of radius 8h^{-1} Mpc. This is consistent with the value, 0.69 ± 0.09, obtained by Saunders *et al.* (1992) from an analysis of clustering in real space. Since σ_8^{opt} for optical galaxies is close to unity, taking the weighted mean of the two IRAS determinations, we infer a relative "bias factor", $b^{IRAS}/b^{opt} \equiv \sigma_8^{IRAS}/\sigma_8^{opt} = 0.65$ on scales of ~ 8 h^{-1} Mpc, with an error of about 25%.

The visual appearance of the galaxy distribution in the QDOT survey (Saunders *et al.* 1991, Moore *et al.* 1992) shows structures of increasing apparent richness and overdensity the further out we look. Nearby there are only a few very rich clusters. At $\sim$ 70h^{-1} Mpc, the "Great Wall" (Geller and Huchra 1989) which contains several rich clusters of galaxies is apparent. Further away, at $\sim$ 100h^{-1} Mpc, there are the most prominent superclusters in the survey, such as Hercules, Aquarius-Capricorn and Horologium. This visual impression is reflected in our quantitative estimates of clustering. For example, the variance of counts-in-cells is largest for cells lying $\sim$ 100h^{-1} Mpc away. Consistent with this, our estimates of the correlation function in concentric shells show a marked increase in clustering strength with shell radius. Most of the "large-scale power" seems to come from structures at distances of $\sim$ 100h^{-1} Mpc.

The apparent increase of clustering strength with distance may be interpreted in at least two ways. It may be due to sampling fluctuations of a distribution with an underlying universal clustering pattern, or it may be due to genuine variations of the correlation function with, for example, galaxy luminosity. Ideally one might distinguish

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between these alternatives by comparing estimates of ξ for galaxies of different luminosity in the *same* volume of space. The shape of the luminosity function, however, precludes an analysis of this sort for samples of widely differing intrinsic luminosities selected with a limiting flux. A slightly different approach, and the one we have followed here, is to compare the cross-correlation functions of QDOT galaxies of different luminosities with the *projected* parent catalogue of IRAS galaxies. Although the cross-correlation function is less sensitive than the autocorrelation function to variations in clustering strength with luminosity, our results show that most of the apparent increase in ξ with distance is likely to be due to sampling fluctuations. Nevertheless, a weak dependence of clustering strength with galaxy luminosity is consistent with our data, which allow an increase of $\sim 20\%$ in clustering length for each decade increase in luminosity.

Finally, we investigated the environment of IRAS galaxies by measuring the cross-correlation of the QDOT survey with a sample of rich Abell clusters. For separations larger than $3h^{-1}$ Mpc, the mean galaxy count falls off with cluster radius slightly less steeply than r^{-2}. The cross-correlation amplitude is larger for clusters with (optical) richness $R \geq 1$ than for clusters with richness $R \geq 0$, but we detect no further increase for richer clusters. On small scales there is a deficit of IRAS galaxies relative to optical galaxies. Although this may be related to Dressler's morphology-density relation, our estimates are uncertain at such small separations because the cross-correlation function is smeared out by peculiar velocities and velocity errors. Our results agree well with those of Strauss *et al.* (1992) who measured the distribution of IRAS galaxies around a sample of six nearby clusters.

In summary, the autocorrelation function of the QDOT survey indicates that IRAS galaxies are less strongly clustered than optically selected galaxies on scales $\lesssim 10$ h^{-1} Mpc. On larger scales, the cross-correlations of Abell clusters with optical and IRAS galaxies, and the similarity of the counts-in-cells variances, suggest that optical and IRAS galaxies have comparable clustering amplitude. The large redshift surveys currently under way or at an advanced planning stage will, in the near future, tighten up some of the results which are marginal even with a survey the size of QDOT. These include the redshift-space distortion of the correlation function and the dependence of clustering strength on galaxy luminosity.

Acknowledgments

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Figure captions

Figure 1 (a) The average redshift-space correlation function for 5 artificial QDOT catalogues constructed from CDM N-body as discussed in the text. The different symbols correspond to different weighting schemes: constant unit weighting (filled triangles); equation (3) with $4\pi J_3 = 3000$ (open squares); and equation (3) with J_3 calculated by integrating the linear theory prediction for $\xi(s)$ with $\Gamma = 0.5$ (open circles) and 0.2 (filled circles). The dashed line shows the linear theory prediction for the CDM ($\Gamma = 0.5$) correlation function. (b) The J_3-weighted ($\Gamma = 0.5$) estimate of the CDM correlation function with 1σ error bars calculated from the scatter between 5 separate artificial QDOT catalogues. The error bars to the left and right of each point are the Poisson errors of the J_3-weighted pair counts and the 1σ error from 100 bootstrap resamplings of one of the catalogues respectively.

Figure 2 (a) Two-point correlation functions for the QDOT redshift survey and artificial catalogues. The filled circles give the QDOT estimate obtained from equations (2b) and (3), assuming the $\Gamma = 0.2$ linear theory prediction for $J_3(s_{ij})$. Error bars show 1σ errors calculated from the J_3-weighted pair counts. (These are similar to the errors found by dividing the survey into four quadrants.) The open circles show the result of allowing explicitly for the effect of number density evolution. The dot-dashed line gives the correlation function corrected for small scale peculiar velocities and velocity measurement errors, obtained by fitting the dot-dash line to the data. The stars give the predictions from the standard CDM model obtained from the N-body simulations illustrated in Figure 1a, while the dashed line gives the (real-space) linear theory prediction for $\Gamma = 0.2$. (b) Two-point correlation functions estimated as in (a) for three subsamples of the QDOT survey, volume limited at $40h^{-1}$ Mpc, $80h^{-1}$ Mpc and $120h^{-1}$ Mpc respectively. The filled and open circles give estimates for the total sample, ignoring and including number density evolution, as in (a), but using the estimator of equation (2a).

Figure 3 Two-point correlation functions in real and redshift space for an ensemble of five $b = 1.5$ catalogues constructed from N-body simulations. The filled and open squares show the mean functions in real and redshift space respectively for fully-sampled catalogues. The open circles show the mean function in redshift space for the corresponding 1-in-6 catalogues. (For clarity, these have been offset slightly to the left.) The error bars represent 1σ errors derived from the scatter in the five independent estimates and agree well with the mean of the Poisson errors derived from the pair counts. The lower curve is a fit to the real-space data while the upper curve shows the result of shifting this same curve vertically by the factor 1.53 implied by equation (10).

Figure 4 (a) The real-space and redshift-space projected correlation functions, Ξ_r and Ξ_s, for QDOT galaxies. Ξ_r is taken from Saunders *et al.* 1992. Error bars on Ξ_s are derived from the scatter between octants. (b) as (a), but for ξ_r and ξ_s.

Figure 5 Two-point correlation functions for QDOT galaxies in three concentric shells

of radii 5-50 h^{-1} Mpc (triangles), 50-100 h^{-1} Mpc (squares) and 100-300 h^{-1} Mpc (circles). The filled symbols are calculated using the Davis and Peebles (1982) estimator, equation (2a), and the open symbols are calculated using Hamilton's (1993) estimator, equation(2b). The error bars give 1σ errors calculated from the J_3-weighted pair counts.

Figure 6 The projected cross-correlation function between the QDOT survey and its fully sampled parent catalogue split by luminosity. The luminosity bins considered correspond to $\log(L/h^{-2}L_\odot) < 9.25, 9.25 - 9.75, 9.75 - 10.25, > 10.25$. Error bars are 1σ from the J_3-weighted pair counts. For clarity, the points have been offset slightly in the horizontal direction.

Figure 7 The Abell cluster- QDOT galaxy cross-correlation function. Results are given for clusters of Abell richness $R \geq 0$ (solid circles), $R > 0$ (open squares) and $R > 1$ (open triangles). The 1σ error bars were derived by splitting the QDOT survey into four quadrants. The dashed line shows a fit to Lilje and Efstathiou's (1988) estimate of the cross-correlation function between Abell clusters and optically selected galaxies.